

# Electromagnetic dipole moments of the Top quark

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Recent measurements like the  $t\bar{t}\gamma$  production by CDF as well as the  $\text{Br}(B \rightarrow X_s\gamma)$  and  $A_{CP}(B \rightarrow X_s\gamma)$  are used to constrain the magnetic and electric dipole moments of the top quark. The  $B \rightarrow X_s\gamma$  measurements by themselves define an allowed parameter region that sets up stringent constraints on both dipole moments. Actually, significantly more stringent than previously reported. The measurement by CDF has a  $\sim 37\%$  error that is too large to set any competitive bounds, for which a much lower 5% error would be required at least. On the other hand, because of the LHC's higher energy (apart from its higher luminosity) the same measurement performed there could indeed further constrain the allowed parameter region given by the  $B \rightarrow X_s\gamma$  measurement.

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## I. INTRODUCTION

The top quark stands out as the heaviest known elementary particle and its properties and interactions are among the most important measurements for present and future high energy colliders [1]. In particular, anomalous top dipole moments could point towards new physics (henceforth NP) effects like a composite nature of the top quark [2]. Concerning the anomalous magnetic and electric dipole moments (henceforth MDM and EDM, respectively) of the top quark, it is well known that the  $\text{Br}(B \rightarrow X_s\gamma)$  can set up the most stringent constraints [3]. (Another possible test of the MDM could come from  $H \rightarrow \gamma\gamma$  [4].) Recently, the CDF collaboration has reported a measurement of  $t\bar{t}\gamma$  production with  $6fb^{-1}$  of data [5]. (Some preliminary study has also been done for the LHC [6].) Such process has been

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considered as a probe of the dipole moments of the top quark by Baur et. al [7] and their overall conclusion was that even though the Tevatron would not be able to set bounds as stringent as those from the  $B \rightarrow X_s \gamma$  measurements, the LHC could. The reason for this is that since the dipole coupling is proportional to the momentum of the photon there is more relative contribution (compared to the QED coupling) as the energy of the collider increases. In this work, we take the experimental result by [5] and make an estimate of the bounds on the MDM and EDM, where indeed we corroborate that  $t\bar{t}\gamma$  at the Tevatron is far from competing with  $B \rightarrow X_s \gamma$ . But on the other hand, we also find that that LHC could in principle set significant *direct* bounds that would further improve what we already have from the *indirect* bounds from  $B \rightarrow X_s \gamma$ .

Following [8], we define the effective  $t\bar{t}\gamma$  Lagrangian

$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t} \left( Q_t \gamma_\mu A^\mu + \frac{1}{4m_t} \sigma_{\mu\nu} F^{\mu\nu} (\kappa + i\tilde{\kappa}\gamma_5) \right) t, \quad (1)$$

where the CP even  $\kappa$  and CP odd  $\tilde{\kappa}$  terms are related to the anomalous MDM and EDM of the top quark, respectively. For instance, the parameter  $\kappa$  is related to the gyromagnetic factor  $g_t$  by  $\kappa = Q_t(g_t - 2)/2$ , or to the  $\mu_t$  MDM parameter as defined in [3] by  $\kappa = 2m_t\mu_t/e$ . Similarly, the EDM  $d_t$  as in [3] is related to  $\tilde{\kappa}$  as  $\tilde{\kappa} = 2m_t d_t/e$ . In the SM, the value of  $\kappa$  is of order  $10^{-3}$  [4], whereas  $\tilde{\kappa}$  is of order  $10^{-15}$  [9]. Given their smallness we shall consider the SM values as zero in this work.

## II. LIMITS FROM $t\bar{t}\gamma$ PRODUCTION AT THE TEVATRON

The CDF collaboration has reported a cross-section measurement of top-quark pair production with an additional photon that carries at least 10 GeV of transverse energy,  $\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08$  pb [5]. In addition, using events with the same selection criteria as for the  $t\bar{t}\gamma$  candidates, but without the photon, they also perform a measurement of the  $t\bar{t}$  production cross section. In this way they determine the ratio

$$R^{\text{exp}} \equiv \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}} = (0.024 \pm 0.009)\text{pb} , \quad (2)$$

in which systematic uncertainties are eliminated. The experimental result (2) is in excellent agreement with the SM prediction  $R^{\text{SM}} = 0.024 \pm 0.005$  [5].

The potential of using  $t\bar{t}\gamma$  production at hadron colliders as a probe of the  $t\bar{t}\gamma$  vertex was studied in [7] (following previous work in [10]). That production process can probe the

charge of the top quark, including the presence of an axial–vector term, if any. The strategy proposed in [7] relies on analyzing the transverse–momentum distribution of the radiated photon, as the  $\sigma_{\mu\nu}q^\nu$  dipole term tends to favor a greater  $p_T^\gamma$ . In this paper we assume that the dimension-4  $t\bar{t}\gamma$  coupling is as dictated by the Standard Model, so that possible NP effects appear in the dipole terms only. Since the main result by CDF is given in terms of  $\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ , we compute that ratio as a function of the MDM  $\kappa$  and the EDM  $\tilde{\kappa}$  to set bounds on those parameters. Although our strategy is much simpler than the analysis carried out in [7], we believe it is yet useful to obtain an estimate of the sensitivity of the Tevatron result, and of future LHC results.

We use CalcHep 3.4 [11] to compute the cross sections for  $p\bar{p} \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$  and  $p\bar{p} \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-\gamma$  at the Tevatron energy, and the same processes with  $pp$  initial state at LHC energies. We apply the cut  $E_T^\gamma \geq 10$  GeV in our calculation, as done in the CDF measurement, which also has the side effect of avoiding infrared behaviors in the computation. In the radiative production process two modes are predominant: (1)  $t\bar{t}$  produced along with the radiated photon followed by the decay of the top pair, which is indeed  $t\bar{t}\gamma$  production proper, and (2)  $t\bar{t}$  produced on-shell with one of them decaying radiatively (such as  $t \rightarrow bW^+\gamma$ ). The first mode may involve initial–state radiation if the initial partons are charged. The second mode may involve final–state radiation from the  $b$  jets, the intermediate  $W$  boson or the  $W$  decay products. By not letting the  $W$  boson decay we are effectively reducing some of the final–state radiation, so that the photon can only be radiated by a top quark, a  $W$  boson or a  $b$  quark. The SM value for  $p\bar{p} \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-\gamma$  at the Tevatron we obtain is 0.093 pb and the SM ratio is thus  $R^{\text{SM}} = 0.018$ . This result is well within the experimental error in (2), although at the low end of the theoretical SM result quoted in [5]. We attribute that lower value to the fact that we are ignoring the diagrams where the photon is radiated from the  $W$  decay products. In order to reduce the impact of that systematic error on our results, we focus our attention on a normalized ratio  $\hat{R} \equiv R/R^{\text{SM}}$ . In this way, the CDF result (2) can be translated to  $\hat{R}^{\text{exp}} = 1 \pm 0.375$ .

On the theoretical side, it is well known that at tree level the SM amplitude is real. The CP–even MDM  $\kappa$  term contributes linearly to the real part of the total amplitude, whereas the CP–odd EDM  $\tilde{\kappa}$  contributes to its imaginary part only. Therefore, the expression for  $\hat{R}$  must have in general the quadratic form  $\hat{R} = 1 + a_1\kappa + a_2\kappa^2 + b_2\tilde{\kappa}^2$ . By computing  $\hat{R}$  for several values of  $\kappa$  and  $\tilde{\kappa}$  we can obtain the coefficients  $a_i$  in  $\hat{R}$  at the desired energy. Then

we use a relation of the form

$$\widehat{R}_1 \leq \widehat{R} = 1 + a_1\kappa + a_2\kappa^2 + a_3\widetilde{\kappa}^2 \leq \widehat{R}_2 \quad (3)$$

to find the allowed parameter region for  $(\kappa, \widetilde{\kappa})$  at that energy. In the case of the CDF measurement (2), we set  $\widehat{R}_{1,2} = 1 \pm 0.375$  to define the allowed region at the  $1\sigma$  level. As for the numerical coefficients we obtain  $a_1 = 0.02, 0.02, 0.16$  for the Tevatron, LHC (7 TeV) and LHC (14 TeV). Similarly,  $a_2 = 0.01, 0.08, 0.107$  and  $a_3 = 0.001, 0.075, 0.116$ .

### III. LIMITS FROM $B \rightarrow X_s \gamma$

In the context of effective lagrangians the  $b \rightarrow s \gamma$  transition occurs through the effective Wilson coefficient  $C_7(\mu)$ , computed at the electroweak scale  $\mu_h \gtrsim M_W$  from loop diagrams where the photon can be emitted either from the  $W$  boson or from the top quark [12]. NP effects on  $C_7(\mu_h)$  can come from several different sources, for instance an anomalous  $WW\gamma$  coupling. In this paper we are interested in the contributions from the MDM and EDM of the top quark to the effective  $t\bar{t}\gamma$  vertex and, for simplicity, those are the only ones we will consider. Furthermore, the QCD running of  $C_7(\mu)$  from the electroweak scale down to the bottom mass scale causes it to mix with other coefficients, so that  $C_7(m_b)$  can receive NP contributions also from non-electroweak anomalous couplings. The main contribution of this type comes from the Wilson coefficient  $C_8(\mu_h)$  associated with the  $t\bar{t}g$  vertex. If we separate the SM value  $C_7^{\text{SM}}(m_b) = -0.31$  from the NP contributions, the form of  $C_7(m_b)$  in terms of the Wilson coefficients evaluated at  $\mu_h$  is [12]

$$C_7(m_b) = -0.31 + 0.67 \delta C_7(\mu_h) + 0.09 \delta C_8(\mu_h) + \dots, \quad (4)$$

where  $\delta C_i = C_i - C_i^{\text{SM}}$  and the ellipsis refers to terms containing other Wilson coefficients that make numerically smaller contributions. As mentioned above, we will focus only on the contributions to  $C_7(m_b)$  arising from the MDM and EDM of the top quark. Thus, in (4) we set  $\delta C_8(\mu_h) = 0$  and keep  $\delta C_7(\mu_h)$  which is given by [8]

$$\begin{aligned} G_2 &= \frac{1}{4} - \frac{1}{x-1} + \frac{\ln x}{(x-1)^2} = 0.0908, \\ G_1 &= \frac{x/2 - 1}{(x-1)^3} (x^2/2 - 2x + 3/2 + \ln x) - G_2 = 0.0326, \\ C_7(\mu_h) &= C_7^{\text{SM}}(\mu_h) + \kappa G_1 + i\widetilde{\kappa} G_2, \end{aligned} \quad (5)$$

with  $x = (m_t/m_W)^2 = 4.63$ . Notice that in (5)  $C_7^{\text{SM}}(\mu_h) = -0.22$  is a real number, as is the CP-even MDM term proportional to  $\kappa$ , but the CP-odd EDM term in  $\tilde{\kappa}$  adds an imaginary part to  $C_7$ . This means that the  $b \rightarrow s\gamma$  width, being proportional to  $|C_7|^2$ , will depend linearly and quadratically on  $\kappa$ , but only quadratically on  $\tilde{\kappa}$ . On the other hand, studies that involve  $b \rightarrow s$  transitions in general have been done that can set bounds on the real part of  $\delta C_7$ :  $-0.15 < \text{Re}(\delta C_7(\mu_h)) < 0.03$  [13]. Since from (5) we get  $\text{Re}(\delta C_7(\mu_h)) = 0.0326\kappa$ , the allowed region for  $\kappa$  would be  $-5 < \kappa < 1$ . This result is consistent with the bounds we obtain below based on the branching ratio for  $B \rightarrow X_s\gamma$ .

### A. Limits from the branching ratio $\mathcal{B}(B \rightarrow X_s\gamma)$

An updated numerical expression for the branching ratio  $\mathcal{B}(B \rightarrow X_s\gamma)$  in terms of the coefficients  $C_7(\mu_h)$  and  $C_8(\mu_h)$  can be found in eq. (4.3) of [14] which, retaining only LO contributions, can be written as

$$\begin{aligned} \delta\mathcal{B}(B \rightarrow X_s\gamma) &\equiv \mathcal{B}(B \rightarrow X_s\gamma) - \mathcal{B}^{\text{SM}}(B \rightarrow X_s\gamma) = 10^{-4} \times \\ &\times \left( \text{Re}(-7.184\delta C_7 - 2.225\delta C_8 + 2.454\delta C_7\delta C_8^*) + 4.743|\delta C_7|^2 + 0.789|\delta C_8|^2 \right), \end{aligned} \quad (6)$$

where  $\delta C_{7,8}$  are defined as in (4) and it is understood that they are evaluated at the electroweak scale  $\mu_h$ . The numerical coefficients in (6) were computed in [14] assuming a cut in the photon energy  $E_\gamma > E_0 = 1.6$  GeV, as is conventionally done in this type of calculations and as will always be assumed in this paper in connection with the process  $B \rightarrow X_s\gamma$ . If the only NP effects we take into account are the MDM and EDM of the top quark, the coefficient  $\delta C_7(\mu_h)$  appearing in (6) is given by (5), and  $\delta C_8(\mu_h) = 0$ .

In order to use (6) to constraint  $\kappa$  and  $\tilde{\kappa}$  we need a predicted value for  $\mathcal{B}^{\text{SM}}(B \rightarrow X_s\gamma)$  and a measured value for  $\mathcal{B}(B \rightarrow X_s\gamma)$ . For  $\mathcal{B}^{\text{SM}}(B \rightarrow X_s\gamma)$  there are three recent calculations referred to in the literature,  $10^4 \times \mathcal{B}^{\text{SM}}(B \rightarrow X_s\gamma) = (2.98 \pm 0.26)$  [15],  $(3.15 \pm 0.23)$  [16], and  $(3.47 \pm 0.48)$  [17]. A thorough discussion of those results can be found in [18]. For concreteness, we use in our calculations the value from [16]. The most recently updated experimental value is  $\mathcal{B}^{\text{Exp.}}(B \rightarrow X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$  [19] (see also the recent status report [20]). With those theoretical and experimental values, from (6) with  $\delta C_7$  as given by (5), we get the relation

$$\delta\mathcal{B}(B \rightarrow X_s\gamma) = (3.43 \pm 0.22) - (3.15 \pm 0.23) = -0.234\kappa + 0.005\kappa^2 + 0.039\tilde{\kappa}^2, \quad (7)$$

which we use to set limits on  $(\kappa, \tilde{\kappa})$ .

### B. Limits from the asymmetry $A_{\text{CP}}(B \rightarrow X_s \gamma)$

The CP asymmetry

$$A_{\text{CP}}(B \rightarrow X_s \gamma) = \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_{\bar{s}} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_{\bar{s}} \gamma)} \quad (8)$$

was first proposed in [21]. Its latest experimental value is quoted in [19] as  $A_{\text{CP}}^{\text{Exp.}}(B \rightarrow X_s \gamma) = (-0.8 \pm 2.9)\%$ . Concerning the SM prediction, the most recent study is [22] whose eq. (11) reads

$$A_{\text{CP}}^{\text{SM}}(B \rightarrow X_s \gamma) = 1.15 \frac{\tilde{\Lambda}_{17}^u - \tilde{\Lambda}_{17}^c}{300 \text{ MeV}} + 0.71. \quad (9)$$

Here  $\tilde{\Lambda}_{17}^u$  and  $\tilde{\Lambda}_{17}^c$  are hadronic parameters associated with the contribution of resolved photons to the asymmetry. Their precise values are not known, but they are expected to be in the ranges  $[-330, 525]$  MeV and  $[-9, 11]$  MeV, respectively [22]. This means that there is a significant uncertainty in the SM prediction,  $-0.6\% < A_{\text{CP}}^{\text{SM}} < 2.8\%$ . We have decided to choose the middle value of 1.1% for which  $\tilde{\Lambda}_{17}^u - \tilde{\Lambda}_{17}^c \simeq 102$  MeV.

An expression for the asymmetry that includes NP effects entering through the Wilson coefficients  $C_i$  with  $i = 1, 7, 8$  is given in eq. (13) of [22]. Since we are assuming  $C_1 = C_1^{\text{SM}}$  and  $C_8 = C_8^{\text{SM}}$  we can rewrite it in a simplified form. With the definition  $C_7(m_b)/C_7^{\text{SM}}(m_b) = r_7 e^{i\theta_7}$  we get

$$A_{\text{CP}}[\%] = a_7 \frac{\sin(\theta_7)}{r_7} + 1.07 \frac{\cos(\theta_7)}{r_7} + \frac{0.03}{r_7^2}, \quad (10)$$

$$a_7 = 16.86 + 2.1 \frac{\tilde{\Lambda}_{17}^c}{10 \text{ MeV}} + 4 \frac{\tilde{\Lambda}_{78}}{100 \text{ MeV}},$$

where the angle  $\gamma$  appearing in [22] has been set to  $\gamma = 66.4^\circ$ , as done in that reference. The term  $a_7$  depends on the unknown hadronic parameters  $\tilde{\Lambda}_{17}^c$  and  $\tilde{\Lambda}_{78}$  that are expected to be in the ranges  $[-9, 11]$  MeV and  $[17, 190]$  MeV, respectively. This implies that  $15.7 < a_7 < 26.7$  and we have decided to set the value  $a_7 \equiv 15.7$ . Taking the minimum value of  $a_7$  will make the asymmetry less sensitive to the CP odd  $\tilde{\kappa}$  term, and the bounds less stringent but more reliable.

With  $C_7(m_b)$  from (4) and  $C_7^{\text{NP}}(m_h)$  from (5), we can write  $r_7 e^{i\theta_7} = C_7(m_b)/C_7^{\text{SM}}(m_b) = 1 - 0.0705\kappa - i0.1962\tilde{\kappa}$ . Substituting that equality in (10) yields

$$A_{\text{CP}}[\%] = \frac{1.1 - 0.075\kappa - 3.08\tilde{\kappa}}{(1 - 0.07\kappa)^2 + 0.0385\tilde{\kappa}^2}. \quad (11)$$

Given the uncertainty range of order 3% of the theoretical prediction as well as the also  $\sim 3\%$  experimental error we have decided to take a conservative view and ask that the NP contribution to  $A_{\text{CP}}$  should at most be of order 4%.

#### IV. ALLOWED PARAMETER SPACE FOR $(\kappa, \tilde{\kappa})$

We can now use (3), (7) and (11) to constrain the allowed region in the  $\kappa$  vs.  $\tilde{\kappa}$  plane. For the asymmetry we require  $|A_{\text{CP}}(X_s\gamma)| < 4\%$ , to be consistent with the uncertainty of the SM prediction as well as the experimental error. The region of allowed values for  $(\kappa, \tilde{\kappa})$  is then determined by (11), and is shown in figures 1, 2 by the gray dashed lines. For the branching ratio, the region allowed at the  $1\sigma$  level is seen from (7) to be bounded by  $-0.038 < \delta\mathcal{B}(B \rightarrow X_s\gamma) < 0.598$ . That region is delimited in figures 1, 2 by gray solid lines. Roughly speaking the MDM is bounded to be  $-2 < \kappa < 1$  which translated to the  $m_t\mu_t = \kappa e/2 = 0.15\kappa$  term used in [3] means that  $-0.3 < m_t\mu_t < 0.15$ . Our limits are significantly more stringent than reported by [3].

The measurement of  $\hat{R}$  at the Tevatron by the CDF collaboration sets limits on  $(\kappa, \tilde{\kappa})$  through (3). As mentioned in section II, the coefficients in that equation were obtained by computing  $\hat{R}$  (with the cut  $E_T^\gamma \geq 10$  GeV) for several values of  $\kappa, \tilde{\kappa}$  with CalcHep 3.4. At the Tevatron energy  $\sqrt{s} = 2$  TeV, the production of  $t\bar{t}$  and  $t\bar{t}\gamma$  receives its dominant contribution from  $u\bar{u}$  initial states, but we took into account also the smaller contributions from initial  $d\bar{d}$  and  $gg$ . For the numerical computation we used the CTEQ 6m parton distribution functions for proton and antiproton as implemented in CalcHep. At the  $1\sigma$  level the allowed region for  $(\kappa, \tilde{\kappa})$  is bounded by the inequalities  $0.625 < \hat{R} < 1.375$ . The lower value turns out to be unattainable, so it does not set any bound. The region delimited by  $\hat{R} = 1.375$  is shown in figure 1 by the black solid line. The black dashed lines in that figure show the regions that would be delimited by hypothetical measurements  $\hat{R} = 1 \pm 0.1$  and  $1 \pm 0.05$ . We see from the figure that, as expected from the analysis in [7], the bounds set by the Tevatron measurement of  $\hat{R}$  are much less constraining than those arising from the asymmetry and

branching ratio for  $B \rightarrow X_s \gamma$ . This is so even in the hypothetical case of an experimental result  $\widehat{R} = 1 \pm 0.1$  with a 10% measurement error. Only a 5% measurement uncertainty could yield bounds of the same order of magnitude at most.

We have also performed the same computation for hypothetical measurements of  $\widehat{R}$  for  $t\bar{t}\gamma$  production in  $pp$  collisions at the LHC, with  $E_T^\gamma \geq 10$  GeV, both at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 14$  TeV. In this case the dominant contribution to the production process comes from  $gg$  initial states, but we also took into account the smaller contributions from the initial states  $u\bar{u}$  and  $d\bar{d}$ . The results are shown in figure 2 (a) for the lower LHC energy and in figure 2 (b) for the higher one. As seen in the figure, the hypothetical experimental results at the LHC would remove significant portions of the region of the  $(\kappa, \widetilde{\kappa})$  plane allowed by the measurements of the branching ratio and  $CP$  asymmetry of  $B \rightarrow X_s \gamma$ . Whereas this is true already at  $\sqrt{s} = 7$  TeV, the constraints set by a measurement of  $\widehat{R}$  at  $\sqrt{s} = 14$  TeV with an experimental uncertainty smaller than, say, 30% would lead to strikingly tighter bounds on  $(\kappa, \widetilde{\kappa})$  than those currently available. Our overall conclusions agree with those given by Baur et. al [7] even though their analysis was not based on the ratio  $R$  reported by CDF but on the change in the  $p_t$  distribution of the photon.

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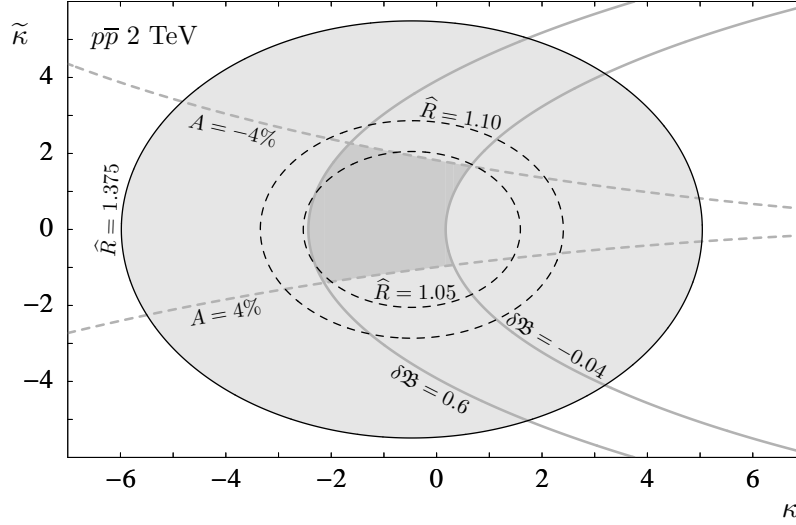


FIG. 1: The allowed parameter space for the anomalous magnetic and electric dipole moments of the top quark. Gray solid lines: region allowed by the experimental results for the branching ratio for  $B \rightarrow X_s \gamma$ , see eq. (7). Gray dashed lines: region allowed by the experimental results for the  $CP$  asymmetry for  $B \rightarrow X_s \gamma$ , see eq. (11). Black solid line: region allowed by the CDF measurement of  $\hat{R}$  for  $t\bar{t}\gamma$  production at  $\sqrt{s} = 2$  TeV,  $E_T^\gamma > 10$  GeV, see eq. (3). Black dashed lines: regions allowed by the values of  $\hat{R}$  indicated in the figure.

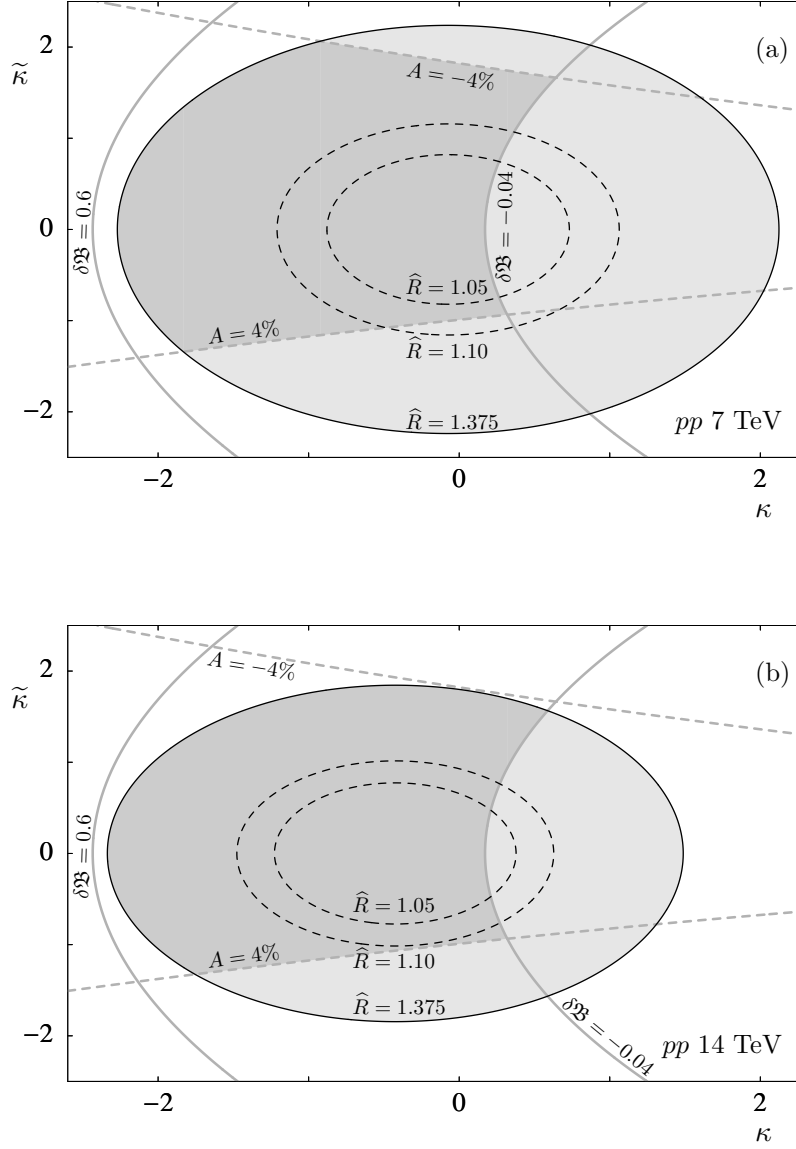


FIG. 2: Gray lines as in previous figure. Black solid and dashed lines delimit the regions allowed by hypothetical measurements of  $\hat{R}$  for  $t\bar{t}\gamma$  production with  $E_T^\gamma \geq 10$  GeV at the LHC at (a)  $\sqrt{s} = 7$  TeV, (b)  $\sqrt{s} = 14$  TeV.